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CARBON FOOTPRINTING

A life cycle greenhouse gas inventory of a tree production system

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Abstract
Purpose This study provides a detailed, process-based life cycle greenhouse gas (GHG) inventory of an ornamental tree production system for urban forestry. The success of large-scale tree planting initiatives for climate protection depends on projects being net sinks for CO_2 over their entire life cycle. However, previous assessments of urban tree planting initiatives have not accounted for the inputs required for tree production in nurseries, which include greenhouse systems, irrigation, and fertilization. A GHG inventory of nursery operations for tree production is a necessary step to assess the life cycle benefits or drawbacks of large-scale tree planting activities.
Methods Using surveys, interviews, and life cycle inventory databases, we developed a process-based life cycle inventory of GHG emissions for a large nursery operation in California, USA.
Results and discussion The inventory demonstrated that 4.6 kg of CO_2-equivalent is emitted per #5 (nominally a 5-gallon) tree, a common tree size produced by nurseries. Energy use contributed 44% of all CO_2-equivalent emissions, of which electricity and propane constituted 78%. Electricity use is dominated by irrigation demands, and propane is used primarily for greenhouse heating. Material inputs constituted the next largest contributor at 36% of emissions; plastic containers contributed just over half of these emissions. Transport emissions accounted for 16% of total nursery GHG emissions. Shipping bamboo stakes from China (43%) and diesel fuel consumed by nursery delivery trucks (33%) were the largest transport emission sources.
Conclusions GHG emissions from the tree production life stage are 20% to 50% of mean annual CO_2 storage rates based on urban tree inventories for three California cities. While considering nursery production alone is insufficient for drawing conclusions about the net climate change benefits of tree planting initiatives, the results demonstrate that nursery production emissions are modest compared with CO_2 storage rates during tree life. Identifying key sources of emissions in the nursery tree production system can help operators reduce emissions by targeting so-called hot-spots. In particular, switching to renewable energy sources, capitalizing on energy and water efficiency opportunities, container light-weighting, and sourcing bamboo stakes from producers closer to the point of use are potential avenues for reduced emissions.

Keywords Carbon footprint · Climate change · Nursery · Tree planting · Tree production · Urban forestry

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1 Introduction

Urban forests in the USA contain 3.8 billion trees and account for nearly one quarter of the nation's total tree canopy cover (Dwyer et al. 2000). City trees mitigate climate impacts by assimilating carbon dioxide (CO_2) in their biomass as they grow and, through shading, evapotranspirational cooling, and wind speed reduction, reducing building energy use and associated greenhouse gas (GHG) emissions from power plants (McPherson and Simpson 1999; Akbari 2002; Nowak et al.

2002; Schwab 2009). Researchers estimate that, depending upon climate, extent of canopy cover, forest age, and species, urban trees in the United States store 700 million tons of carbon (equivalent to 2,570 tons CO_2) as a long-term sink and currently sequester 23 million tons of carbon each year (equivalent to 84 tons CO_2) (Nowak and Crane 2002).

Over the past several years, mayors of nine large cities in the USA have launched major tree planting initiatives with pledges to collectively plant nearly 11 million trees (McPherson and Young 2010). In many cases, these initiatives are embedded within municipal climate protection plans and sustainability agendas. For example, the day following his election as mayor of the city of Los Angeles, Antonio Villaraigosa planted a tree, kicking off his plan to plant 1 million trees in the next several years and said, "Los Angeles, the dirtiest big city in America, has the opportunity to be the greenest" (Hymon and Merl 2006). The tree initiative was dubbed Million Trees LA and is integral to the city's climate action plan, which aims to reduce greenhouse gas emissions 35% below 1990 levels by 2030 (City of Los Angeles 2007). Over a 35-year planning horizon, the 1-million-tree planting was projected to reduce atmospheric CO_2 by about 1 million t (McPherson et al. 2011). A relatively small amount of CO_2 was projected to be released during tree care and decomposition of dead biomass (102,000 tons).

The Climate Action Reserve's (CAR's) Urban Forest Project Protocol provides potential financial benefits in the form of offset credits to local governments for their tree planting activities (CAR 2010). Fungible offsets are certified by CAR only after third-party verification confirms that projects have followed the protocol's guidance and have accurately reported CO_2 reductions. The scope of accounting is limited to CO_2 sequestration and release associated with tree care activities. The Protocol has set the stage for significant investment in large-scale urban tree planting projects and has challenged urban forestry professionals to achieve higher levels of performance from their trees through planning, implementing best practices, and conducting long-term monitoring.

The success of large-scale tree planting initiatives for climate protection depends on projects being net sinks for CO_2 over their entire life cycle. In order to understand the life cycle benefits or drawbacks of large-scale tree planting activities, a GHG inventory of nursery operations for tree production is required. However, previous assessments of urban forestry initiatives have not accounted for the inputs required for tree production in nurseries, which include potentially significant sources of GHG emissions such as greenhouse systems, irrigation, and fertilization.

This study provides the first detailed, process-based life cycle greenhouse gas inventory of an ornamental tree production system, supported by field data from Monrovia Nursery in Woodside, CA, and its key suppliers. Understanding the nursery production system is a key step to understanding the full life cycle implications of urban forestry programs.

Some previous assessments have examined similar or related tree production systems. Life cycle studies exist for seedling production in forestry operations (Aldentun 2002; CORRIM Inc. 2004; Berg and Lindholm 2005; Sonne 2006; Fan et al. 2010). Altdentun found that CO_2 emissions from seedling production in Sweden ranged between 47 and 133 kg CO_2 per 1,000 seedlings but did not include emissions of N_2O from fertilizer or any other non-CO_2 GHGs. The wide range in outcomes was due, in part, to differences in seedling residence time in nurseries between northern and southern Sweden. Residence times for forestry seedlings are significantly shorter than those for ornamental seedlings used in urban forestry.

Two life cycle inventories were also developed for forestry seedlings in the USA. These inventories were accessed through the GaBi Professional database but are based on work done by CORRIM and the USLCI initiative (PE International 2009; National Renewable Energy Laboratory 2008; CORRIM Inc. 2004). These inventories indicate a range of 29 to 40 kg CO_2-equivalent (CO_2e) per 1,000 seedlings, about half that of the Swedish estimate despite the inclusion of non-CO_2 GHGs.

Other studies have been conducted for tree production systems. Heller et al. (2003) considered the production of willows (*Salix* sp.) used in short-rotation bioenergy cropping systems and found that biomass production systems resulted in 55 units of biomass energy per unit of fossil energy consumed over a 23-year lifetime, supporting the belief that willow biomass crops are a sustainable biomass energy crop from an energy return perspective. Couillard et al. (2009) compared the production of natural and artificial Christmas trees and found that natural Christmas trees performed better from a climate change perspective but not as well in other categories of analysis such as ecosystem quality.

Other studies have considered greenhouse production systems that produce flowers and roses, but not trees (Russo and Zeller 2008). In these greenhouse studies, diesel fuel and fertilizer-related emissions were the primary atmospheric burdens. Despite these previous studies of related or similar production systems, none have addressed ornamental tree production.

2 Methods

2.1 Goal and scope

The purpose of this GHG life cycle inventory (LCI) is to generate the first detailed inventory for nursery operations producing containerized trees for urban forestry programs.

We expect this inventory to be used in life cycle GHG assessments of urban forestry.

The scope of our analysis constitutes a cradle-to-retailer GHG inventory that includes material and chemical inputs, electricity and fuel use, and transportation of inputs and products for a nursery and its suppliers. The functional unit of study is a #5 tree (#5 is trade size, sold nominally as 5-gallon, although its actual size is about 4-gallons) at the site of retail; however, we also report results in equivalent units (EQUs). EQUs are used by some nursery operations to track the costs associated with producing different products, namely different-sized trees. EQUs can be related to the following containerized tree products: #1 (nominally 1-gallon) tree=1 EQU, #5 (nominally 5-gallon) tree=5.5 EQU, #7 (nominally 7-gallon) tree=9.1 EQU, and #15 (nominally 15-gallon) tree=18.4 EQU. By reporting study outcomes in per-EQU, the GHG inventory can be used to evaluate the performance of additional tree product sizes not considered in our own study.

The production of capital equipment and facilities used in tree production operations are not considered in this inventory. Figure 1 defines the system analyzed in the study and shows the months required for each step of production for a #5 tree.

2.1.1 System definition

The functional unit for the tree production system in this study is a #5 tree (5.5 EQU), though we report results on per-year basis, which can be translated into a per-EQU basis as well. Information on materials and energy consumed during tree production was provided by Monrovia Nursery for the year 2009. Monrovia is one of the largest wholesale growers in the USA with nurseries in Oregon, Georgia, North Carolina, and California. As demonstrated in Fig. 1, the production process for a #5 tree requires just over 4 years. During this period, the seedling will move from greenhouse to outdoor growing spaces. At each growth stage through the grafting step, a portion of the seedlings are lost. These losses are accounted for in this analysis.

2.2 Life cycle inventory

Nursery operations were divided into categories for the purposes of data collection and developing the LCI model. The following section describes how each category was modeled in the life cycle inventory. All datasets adapted from LCI databases were accessed through the GaBi software tool (PE International 2009), and other datasets were adapted directly from reports and publications.

Data collection required interviewing and surveying representatives of Monrovia Nursery and their suppliers. Monrovia Nursery provided data on fuels and electricity used on site broken down by fuel type, and application to production activities, greenhouse activities, irrigation, and buildings (office, docks, shop, and canning; personal communication with Nathan Morrill and Kevin Kohnen, Monrovia Nursery, 15 November 2010). In addition, the nursery provided annual data for container use, agrochemical use, potting soil use and constituent materials, and total annual production in EQUs. Supplier contacts provided key data on production and transport of nursery materials.

2.2.1 On-site and direct energy use in nursery

Electricity consumption in all nursery buildings, including offices, was reported by Monrovia Nursery. To model life cycle GHG emissions for electricity, data for delivered

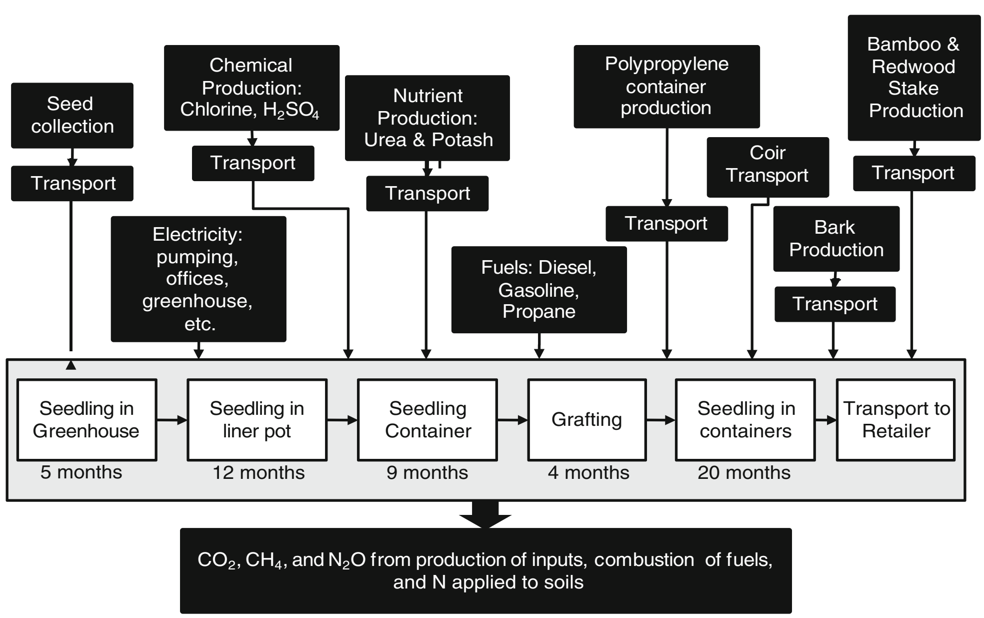

Fig. 1 Nursery system diagram for a #5 tree

electricity from the Western US grid were taken from the USLCI database accessed through the GaBi software tool (National Renewable Energy Laboratory 2008).

Transportation and equipment fuels including diesel and gasoline consumption in nursery trucks, tractors, and equipment were also tracked. Data for production (National Renewable Energy Laboratory 2008) and combustion (CCAR 2009) were combined to estimate total fuel cycle emissions.

On-site propane use, mostly used for heating operations in the greenhouse, was provided along with information on propane transport by the Monrovia Nursery's propane supplier (personal communication with Dennis Parker, Delta Liquid Energy, 23 October 2010). Transport occurs in a propane-fueled truck. As with the diesel and gasoline, total fuel cycle emissions from propane were estimated by combining datasets for production (PE International 2009) and combustion (CCAR 2009).

2.2.2 Potting mix

Potting mix includes bark, manure, and coir. Bark production was modeled based on data from Johnson et al. (2005), representatives of Superior Soil Supplements, and Brady trucking Co. (personal communication with Andria Fike, Superior Soil Supplements, 12 October 2010; personal communication with Paul Mortensen, Brady Trucking Co., 30 March 2011). Brady Trucking also provided data on bark transport. Bark is a co-product of saw-log forestry operations and requires diesel fuel, lubricants, electricity, nitrogen fertilizer, and phosphate. A volumetric allocation was used. Life cycle diesel fuel emissions and electricity are modeled as described in "Section 2.2.1"; lubricant emissions are taken from the Ecoinvent database; US nitrogen fertilizer production is taken from the GaBI US Professional Database, and US phosphate production is taken from the Ecoinvent database (Ecoinvent Centre 2008; PE International 2009). The bark used at the nursery is known to be transported 145 km (90 mi) by truck and 1,127 km (700 mi) by train; both transport modes are modeled using the USLCI database as reported in GaBi.

Both chicken manure and coir were treated as low-value by-products of other production processes. Neither requires significant processing before use in the potting mix. Thus, only transport of these materials was considered in our analysis.

The chicken manure is a by-product from broiler chicken production. The manure is known to be transported by truck from a local supplier at a round-trip distance of 87 km (54 mi). Truck transport is modeled as described in "Section 2.2.1." N_2O emissions from the nitrogen content in chicken manure and other inputs with appreciable N-content are described in "Section 2.2.6."

Coir is a by-product of coconut processing. It is transported from Pollachi to Tuticorin Harbor, India, via truck. At the harbor, it is shipped in a container via a feeder vessel to Singapore harbor and then via a larger vessel to the Port of Long Beach in California (personal communication with Ram Ramakrishnan, SAI, 26 Oct. 2010). The truck operated in India is modeled using the California-based data described earlier, which is a shortcoming of this study as no LCI data on Indian truck operation or freight was found. The feeder vessel and barge were both modeled using a global average dataset from the Ecoinvent database for transoceanic shipping (Ecoinvent Centre 2008).

2.2.3 Synthetic fertilizers and chemicals used in production

Urea, urea ammonium nitrate (UAN 36-0-0), and potassium sulfate (0-0-52) are used in production. Production of these fertilizers as well as their transport to the nursery is accounted for in the study. Emissions for production of these fertilizers are taken from the Ecoinvent database. US production was modeled for the nitrogen fertilizers, urea, and UAN, but European average data was used for potassium sulfate due to a lack of US data. Transport distances and truck types (engine size and brand) were provided by suppliers and are modeled using the diesel production emissions based on the USLCI database and CCAR data for combustion emissions. Emissions from train transport are taken from the USLCI database as reported in GaBi.

Chlorine is used in the production system for disinfection purposes. The transport distance for chlorine to the nursery is unknown, so it is not included in the study. Production is modeled using the GaBi Professional US Extension Database (PE International 2009). Chlorine use constituted a small input to the production system.

2.2.4 Consumables used in production

Plastic containers and stakes are both used in large quantities for tree production. Production of plastic flats, rose pots, and tree containers are all included. Containers are all assumed to be made of injection-molded polypropylene and are sourced from four suppliers, at distances of 80 km (50 mi) to 724 km (450 mi) from the nursery, and shipped by truck to the nursery. The suppliers provided data on total distance traveled and the fuel economy of their trucks. Emissions from truck transport are modeled as described in "Section 2.2.3."

Emissions factors for container production were created by combining USLCI data on US polypropylene production and Ecoinvent data from Europe on injection molding.

Both bamboo and redwood stakes are used in nursery production. Data for bamboo production are adapted from a study on bamboo for use as a building material (van der

Lugt et al. 2006). Van der Lugt et al. found that production and processing of bamboo make up only 4.8% of environmental loads associated with bamboo; the balance is attributable to transportation. Because van de Lugt et al. only report a summary environmental load indicator based on monetization of environmental impacts, we cannot directly use their study's outcome. Instead, we assume that total production-related GHG emissions are equivalent to 4.8% of transport-related emissions, which is based on the findings reported in van de Lugt et al.

Transport-related emissions for bamboo stakes are based on information provided by the supplier but are not complete. Bamboo is produced and processed and shipped to the port of Hong Kong. This first transport link from the production site to the port is unknown. From the port of Hong Kong, the stakes are shipped to the port of Oakland on a transoceanic container vessel. The container is then shipped by truck to Antioch, CA, and then on to the nursery site in Woodlake, CA. Emissions factors for the ocean-going vessel and truck transport are calculated as described for coir in "Section 2.2.2."

Redwood stakes are produced domestically, but no datasets for processed redwood are available. Instead, we use LCI data on surfaced dried hardwood lumber, based on a study by Puettmann and Wilson (2005) as reported in the USLCI. Redwood stakes are transported by truck a one-way distance of 700 km (736 mi), and truck type and fuel economy were provided by the stake supplier. Total fuel cycle emissions are calculated as described in "Section 2.2.1."

2.2.5 Seed collection

Seed purchased by the nursery is provided by suppliers who harvest seeds from trees already growing in the environment. Thus, acquisition burdens are limited to the trucks used to travel to different seed collection sites and deliver seeds to the nursery. Based on information provided by one of two suppliers to the nursery, approximately 2,800 L (740 gal) of gasoline is burned to provide the nursery with seeds each year (personal communication with Doug Lee, Ojai Valley Seed, 20 Oct. 2010). Similar to diesel truck emissions described previously, fuel production is modeled using the USLCI dataset for US gasoline production, and emissions from combustion are estimated using CCAR emissions factors.

2.2.6 Emissions from soils

Emissions from potting and natural soils were also considered in this inventory but were limited to N_2O emissions from fertilized soils. Carbon dioxide emissions from the decay of organic matter used in potting mixes were not considered within the system boundary of this study. This is consistent with GHG inventory practices because bark, coir, and chicken manure all constitute biogenic sources of CO_2 (British Standards Institute 2008).

N_2O emissions were calculated using the Intergovernmental Panel on Climate Change's Tier 1 methods (Intergovernmental Panel on Climate Change 1996). Potting mixes and greenhouse systems are different than typical field-based agriculture and forestry, the intended application of Tier I estimates. Nevertheless, these methods were chosen because no other estimates of N_2O emissions from nursery operations were found.

To apply Tier I methods, estimates of N-content in materials is required. The N-content in synthetic fertilizers is easily calculated based on reported N-content by manufacturers. For the organic sources of N, manure, and coir, research was conducted to estimate N-content by mass. Coir contains approximately 0.5%N by dry weight (Bethke 2008), and an estimate of 1.55% was used for the N content of chicken manure (Sloan et al. 1996).

2.2.7 Co-product allocation

This assessment considers the entire nursery operation and requires an allocation step to attribute inputs and outputs to a particular production unit, here, a #5 tree. While the ISO and many experts recommend avoiding allocation by subdivision or system expansion, neither of these methods can be applied to this production system. Subdivision is not possible because the nursery operates as an integrated system, and data collected by nursery operators cannot be subdivided and assigned to particular (sub)processes attributable to a specific product. System expansion is not possible because no suite of substitutable products could be identified for the other products produced in the nursery, namely many different-sized trees. Thus, an allocation step is a requirement to determine the life cycle inventory for nursery products.

The nursery evaluated in this study has historically tracked production in EQUs. This unit can be translated into different products based on a scaling factor, as described in "Section 2.1." EQUs are used, in part, to help producers determine the cost or burdens of production for different-size trees sold by the nursery. EQUs will thus inform pricing for the final product. EQUs seem preferable than allocation based on physical properties of the trees because they reflect the effort required by the producer (e.g., chemical and material inputs and the greenhouse and outdoor space required over time), rather than mass which does not increase linearly with inputs and time in the nursery. The nursery produced approximately 13,000,000 EQUs in 2009. The functional unit of one #5 tree (5.5 EQUs) is calculated by multiplying total GHG emissions by 5.5 EQUs/ 13,000,000 EQUs.

2.3 Impact assessment

The impact assessment is limited to applying global warming potentials (GWP) to the three primary GHG emissions: CO_2, CH_4, and N_2O, as this study evaluates only GHG emissions. GWPs are based on the 100-year time horizon from IPCC's Fourth Assessment Report and equate to 25 for CH_4 and 298 for N_2O (Intergovernmental Panel on Climate Change 2007).

3 Results and discussion

3.1 Results

Results for the inputs to the nursery production operations are shown in Table 1. These inputs are reported in total annual requirements for the nursery and total requirements per #5 tree. Transportation-related requirements are reported either in volume of diesel consumed, or freight transport units of t-km (ton-kilometers) or kt-km (kiloton-kilometers). The use of volume of fuel units versus t-km units reflect the kind of information provided by suppliers, which either facilitated direct calculations of fuel or only provided the distance traveled of goods.

Key users of energy inputs include irrigation, which accounts for 85% of electricity use, and radiant heating of the nursery's large greenhouse, which is responsible for 94% of propane use.

GHG emission results are presented in Table 2 for each input to the production system and are reported for 1 year production of 13,000,000 EQUs and per 5-gal tree. Total annual GHG emissions of 10,837 tons CO_2e result in an emission rate of 0.83 kg per EQU. Emissions for typical #5 and #9 trees are 4.6 and 15.3 kg, respectively.

Table 1 Annual inputs and transportation requirements for nursery operations

Input	Per nursery-year	Unit	Per #5 tree	Unit
Electricity	3,550	MWh	1.5	kWh
Propane	1,100	kL	0.47	L
Diesel (on-site use)	53	kL	0.02	L
Diesel (transport of product to retail)	98	kL	0.04	L
Diesel (delivery of fuels to nursery)	68	kL	0.03	L
Gasoline	230	kL	0.1	L
Containers	420	t	0.18	kg
Stakes (redwood)	40	t	0.02	kg
Diesel for truck transport	11	kL	4.8×10^{-3}	L
Stakes (bamboo)	260	t	0.11	kg
Oceanic transport by ship	7.9	kt-km	3.3×10^{-3}	t-km
Diesel for truck transport	4.9	kL	2.1×10^{-3}	L
Bark	5,500	t	2.3	kg
Overland transport by train	3,100	kt-km	1.3	t-km
Overland transport by truck	400	kt-km	0.17	t-km
Manure	1,200	t	0.5	kg
Diesel for truck transport	1.8	kL	7.8×10^{-4}	L
Coir	18	t	7.7×10^{-3}	kg
Overland transport by truck	18	kt-km	7.5×10^{-3}	L
Oceanic transport by ship	310	kt-km	0.13	t-km
Urea (46-0-0)	11	t	4.8×10^{-3}	kg
Overland transport by truck	0.13	kL	5.7×10^{-5}	L
Overland transport by train	16	kt-km	6.7×10^{-3}	t-km
Potassium sulfate (0-0-52)	190	t	0.12	kg
Diesel for truck transport	1.6	kL	6.8×10^{-4}	L
Overland transport by train	330	kt-km	0.14	t-km
UAN (36-0-0)	180	t	0.77	kg
Diesel for truck transport	1.0	kL	4.3×10^{-4}	L
Chlorine	2.4	t	1.0×10^{-3}	kg
Seeds	50	kg	2.1×10^{-3}	kg
Diesel for truck operation	2.8	kL	1.2×10^{-3}	L

Table 2 CO_2e Emissions for total nursery output per year and per #5 tree

Category	t CO_2e per year for nursery	kg CO_2e per #5 tree	% of total
Energy use on site	4,802	2.03	44
Electricity	2,020	0.85	19
Diesel	165	0.07	2
Gasoline	664	0.28	6
Propane	1,954	0.83	18
Materials	3,876	1.64	36
Containers	1,514	0.64	14
Stakes	45	0.02	0.4
Bark	1,168	0.49	11
Fertilizers	1,145	0.48	11
Chlorine	4	1.85E-03	0.0
Material transport	1,729	0.73	16
N_2O from potting mix and fertilizer	430	0.18	4
Synthetic fertilizer	333	0.14	3
Manure	96	4.07E-02	0.9
Coir	4.78E-02	2.02E-05	0.0
Total	10,837	4.6	100

The largest contributor of emissions, direct energy use (fuels and electricity consumed on-site) by the nursery, constitutes nearly 50% of CO_2e. Electricity and propane dominate this source of emissions, demonstrating that efficiencies in electric power generation, water use, and irrigation technologies could be potential strategies for reducing GHG emissions from nursery operations.

Propane accounts for 41% of total energy emissions. This finding demonstrates the importance of considering greenhouse operations in the life cycle of agricultural and horticultural products.

Figure 2 shows the breakdown for emissions for materials. Production of materials used in nursery operations are the second largest contributor at 36% of total CO_2e emissions and are dominated by container production (14%), followed by fertilizers and bark (both 11%).

CO_2e emissions from containers even exceeded the GHG emissions associated with fertilizer production, delivery, and N_2O emissions after application. Potential CO_2e emission reductions could be gained from container designs that reduce or eliminate polypropylene mass, or by increasing the number of times containers may be reused in operations, as the nursery already reuses containers.

Transport of materials accounted for 16% of total GHG emissions, and its breakdown by category is shown in Fig. 2. The single greatest source was shipping bamboo stakes from China, which is included in the stakes category. Access to a local source for bamboo stakes could significantly reduce these CO_2e emissions. Diesel emissions associated with the delivery of trees to retail nurseries, and to a lesser extent, the delivery of fuel to the nursery, accounted for 32% of total transport emissions. A more fuel-efficient fleet of delivery vehicles could reduce these transport emissions.

3.2 Discussion

Production emissions for trees used in urban forestry are 4.6 and 15.3 kg for a typical #5 and #9 tree, respectively. These emissions are more than 100 times higher than those associated with seedling production for forestry operations, estimated at 0.029–0.133 kg per seedling (CORRIM Inc. 2004; Aldentun 2002). This result is not entirely surprising because ornamental trees used in urban forestry remain in the nursery much longer, on the order of 4 to 5 years.

Are the life cycle CO_2e emissions for tree production greater than CO_2 stored by a tree planted in an urban environment? If so, large-scale tree planting initiatives may result in net CO_2 emissions, not storage, even during the life of the tree. To address this question, the average annual

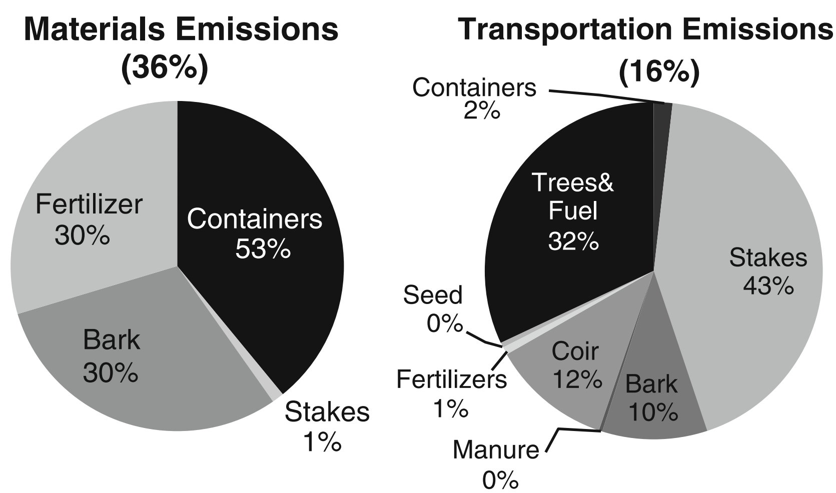

Fig. 2 Breakdown of emissions sources for materials and transportation

CO_2 uptake per tree from municipal forests in several California cities are compared with per-tree CO_2e emissions for tree production.

Ground sampling of 675 randomly located 10×10 m plots in Sacramento County resulted in species identification, measurements, and carbon calculations for 445 trees. Inferring from the sample, Sacramento's 6,043,000 trees sequestered on average 39.4 kg CO_2 per tree each year (McPherson 1998). A similar study of street and park tree populations in Modesto (91,179 trees) and Santa Monica, California (29,229 trees) reported average annual sequestration rates of 96.0 and 41.7 kg per tree, respectively (McPherson and Simpson 2002). Differences in species composition, age structure, tree health, and management practices account for the wide range in mean sequestration rates.

Results from these three cities indicate that CO_2e emission rates for the tree production life stage are 20% to 50% of the mean annual storage rates. Although nursery production of these ornamental trees emits far more CO_2e compared with forestry seedling production, nursery operations are still small compared with CO_2 stored in tree biomass. However, it is premature to conclude that tree planting initiatives are net CO_2e sinks. More research is needed to document the range of GHG emissions associated with different tree planting and management regimes throughout their entire life cycle, including survival rates for different-size trees and the fate of tree biomass at the end-of-life. Trees that are allowed to grow larger in nursery conditions have better survival rates, for example, but require more inputs during the production stage. These kinds of trade-offs should be considered in future research.

4 Conclusions

One of California's largest tree nurseries was estimated to release 10,837 tons CO_2e in 2009, or 4.6 and 15.3 kg for a typical #5 and #9 tree, respectively. This amount is relatively small compared with average annual CO_2 uptake rates by established trees that ranged from 39 to 96 kg. Although these findings suggest that CO_2 removed from the atmosphere during the course of one growing season by an established tree more than offsets emissions from production of that tree, other factors need to be considered. The authors are engaged in a life cycle assessment of each stage that will include emissions from tree care activities and reduced emissions from energy savings. Also, it should be noted that trees provide other environmental, social, and economic benefits whose monetized annual value usually exceeds management costs (McPherson et al. 2005).

Direct energy use in nursery operations was the single largest contributor to nursery emissions, constituting nearly half of all emissions. Electricity used to power pumps for irrigation and, to lesser extents, lighting and air conditioning systems, is the largest energy-related emission source and an important leverage point. Generating on-site renewable electricity, such as using photovoltaic panels, improving irrigation efficiencies, and reducing irrigation water demand could reduce energy-related GHG emissions. Propane consumed to heat the large nursery greenhouse is the second largest emitter of GHGs. Substituting a renewable energy source for propane may be an option for reducing energy emissions along with improving insulation of the heated space.

Production of materials was the second largest contributor to emissions (36%), with containers accounting for 53% of material emissions. Monrovia reuses containers, so emission reductions from a more aggressive reuse or recycling program are limited. Greater potential CO_2e emission reductions could be gained from using containers manufactured with alternative lower-emission resin materials or by reducing polypropylene mass in containers.

Transport emissions accounted for 16% of total nursery GHG emissions. Shipping bamboo stakes from China and diesel fuel consumed by delivery trucks were the largest transport emission sources. Locally sourced bamboo has potential to substantially reduce oceanic transport emissions.

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